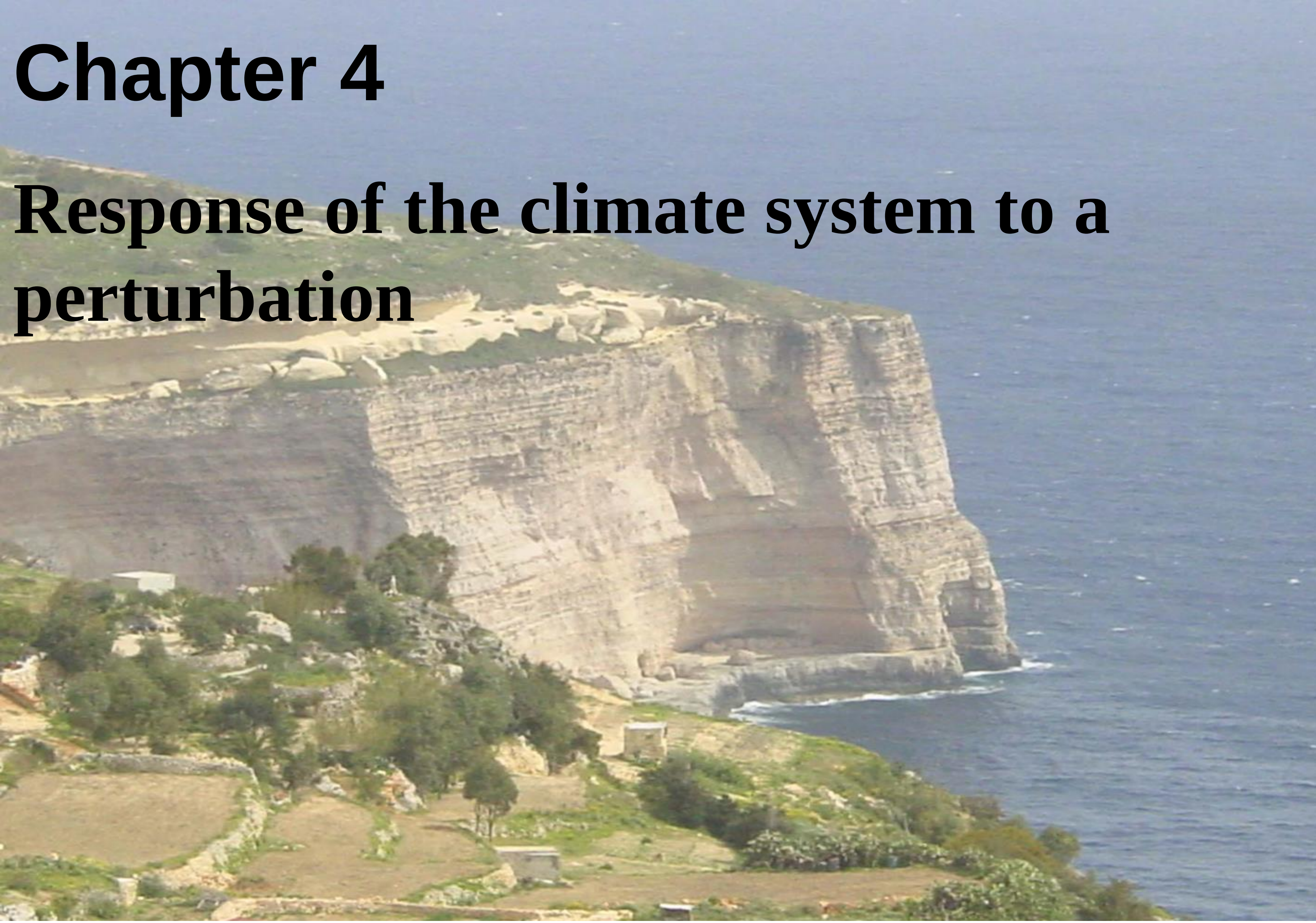


Chapter 4

Response of the climate system to a perturbation

Climate system dynamics and modelling **Hugues Goosse**

Outline

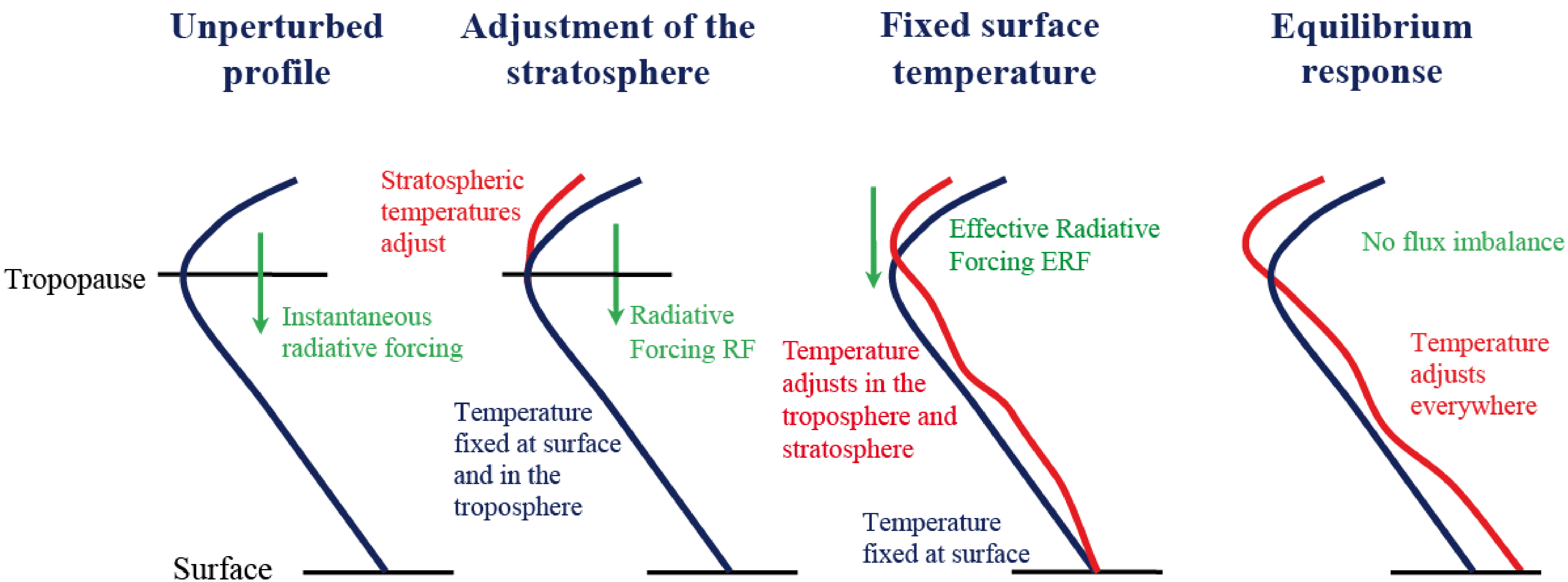
Notion of forcing and feedback.

Description of the standard physical feedbacks.

Analysis of the interactions implying jointly the energy balance, the hydrological and the biogeochemical cycles.

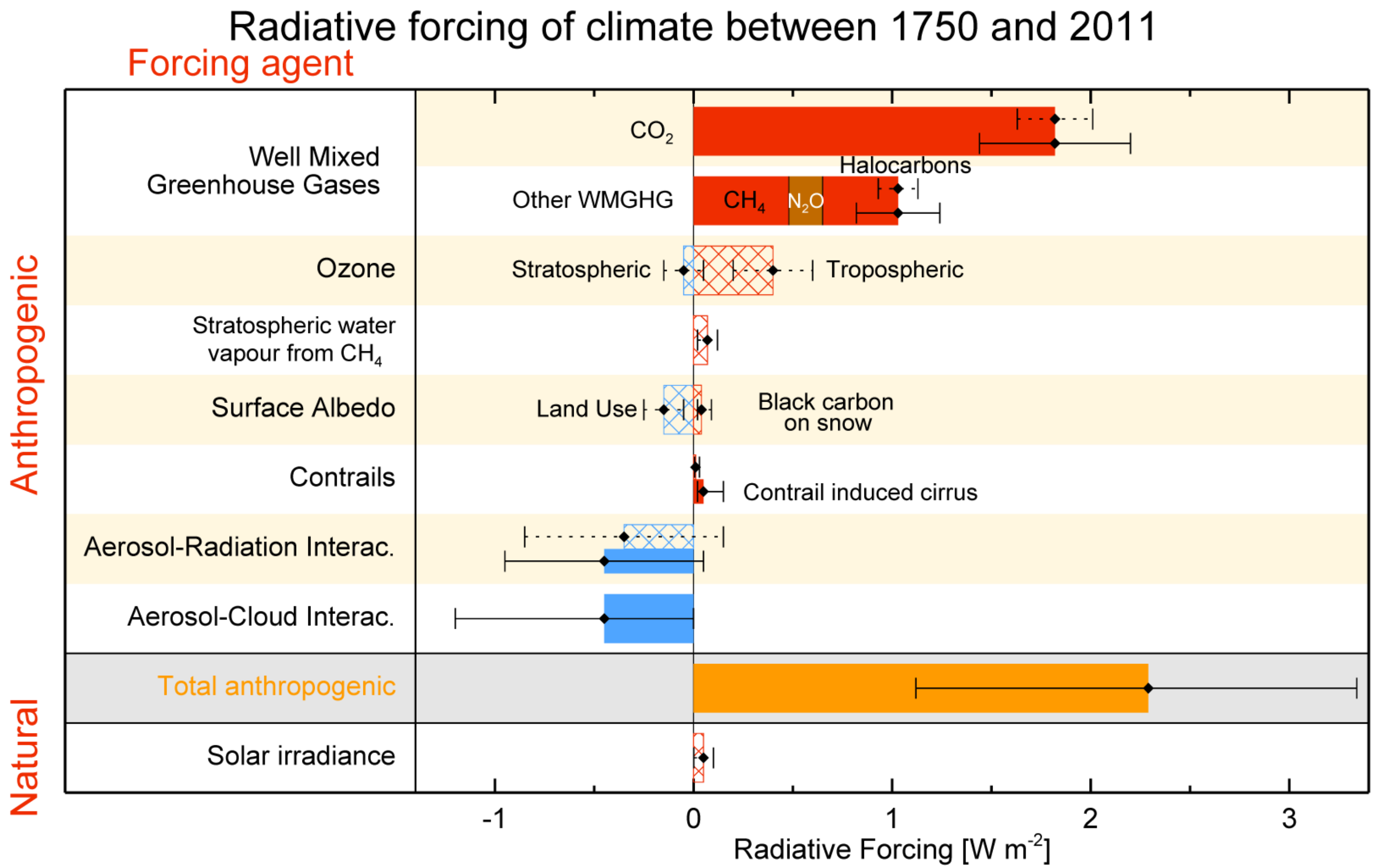
Notion of radiative forcing

To compare the effect on the climate of different perturbations, it is convenient to estimate their effect on the Earth's radiative budget.



Major Radiative forcing agents

Greenhouse gases



Radiative forcing (RF, hatched) and effective radiative forcing (ERF, solid) between 1750 and 2011 for individual forcing agents and the total anthropogenic forcing. Figure from Myhre et al. (2013).

Major Radiative forcing agents

Greenhouse gases

Relatively good approximations of the radiative forcing ΔQ can be obtained from simple formulas:

$$\Delta Q = 5.35 \ln\left(\frac{[CO_2]}{[CO_2]_r}\right)$$

$$\Delta Q = 0.036\left(\sqrt{[CH_4]} - \sqrt{[CH_4]_r}\right)$$

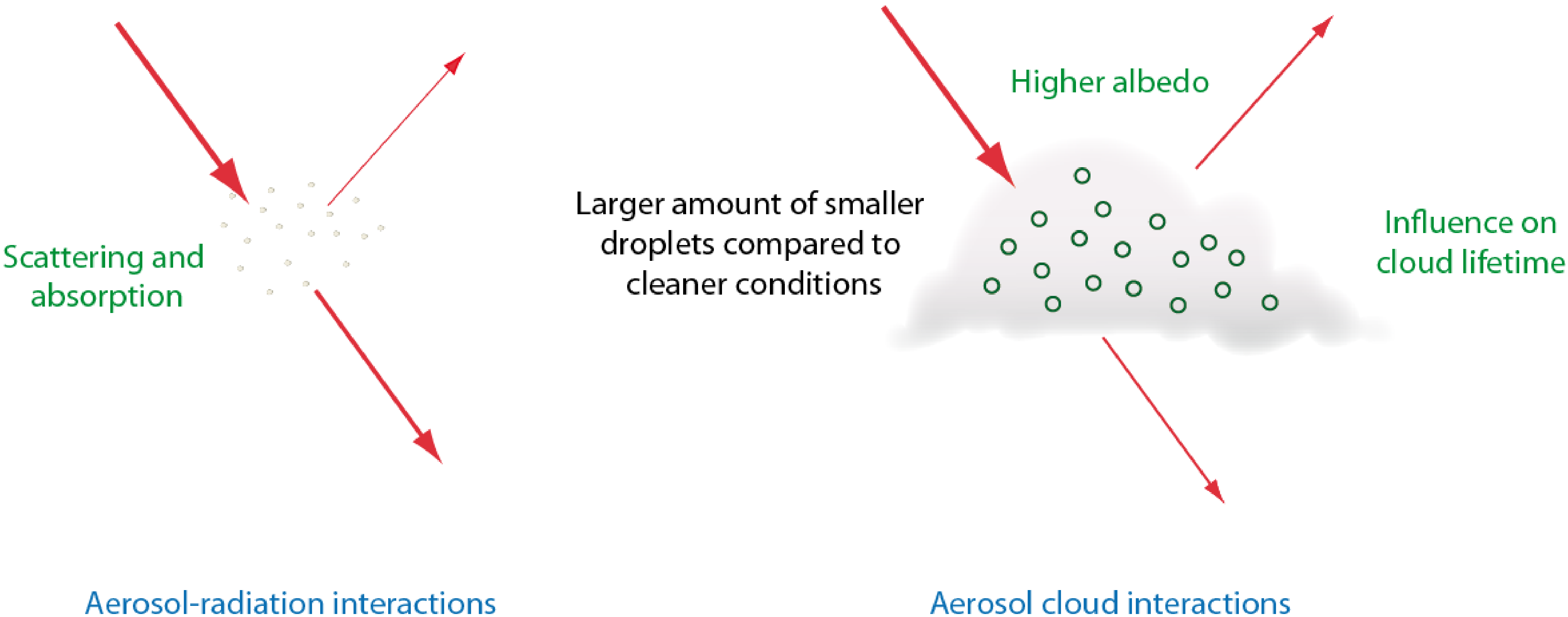
$$\Delta Q = 0.12\left(\sqrt{[N_2O]} - \sqrt{N_2O_r}\right)$$

$[CO_2]$ and $[CO_2]_r$ are the CO_2 concentrations in ppm for the period being investigated and for a reference period, respectively. The units for the other concentrations are ppb.

Major Radiative forcing agents

Aerosols

Atmospheric aerosols are relatively small solid or liquid particles that are suspended in the atmosphere.

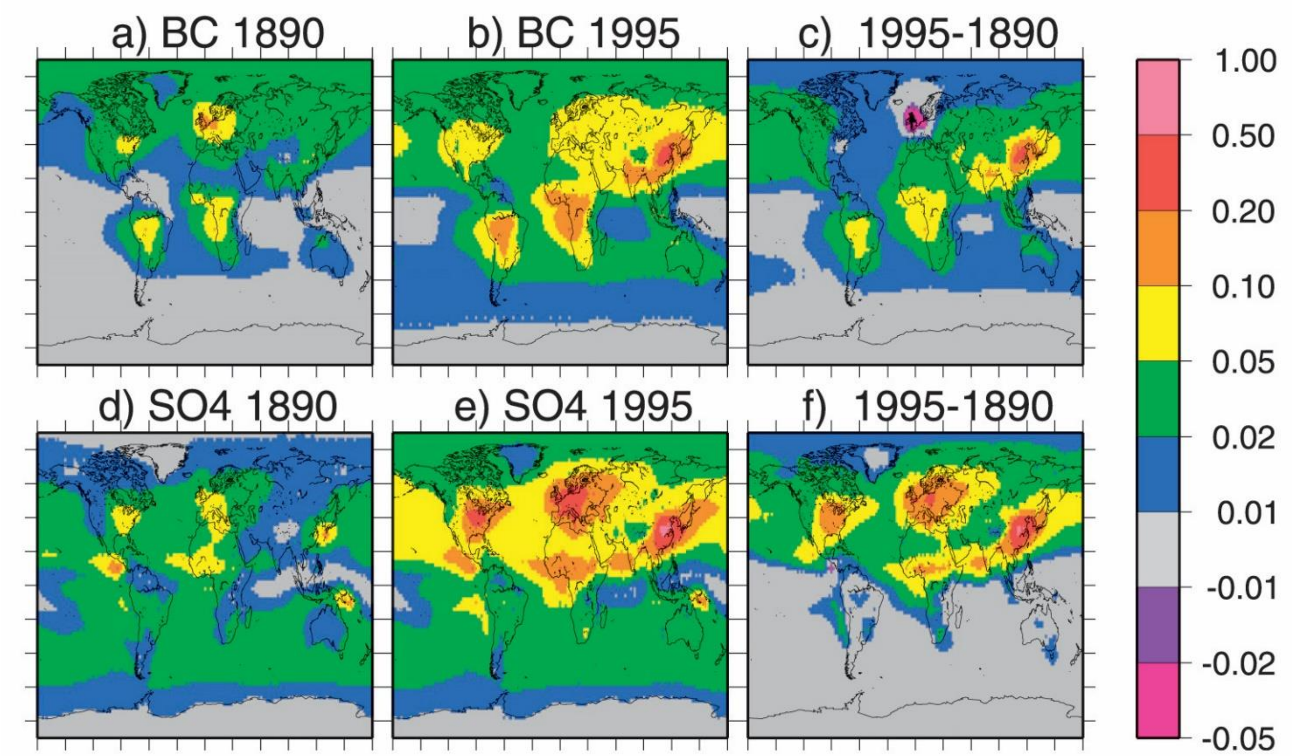


Schematic representation of some aerosol-radiation interactions and aerosol-cloud interactions, focusing on the influence on solar radiation..

Major Radiative forcing agents

Aerosols

Anthropogenic aerosols are mainly concentrated downwind of industrial areas.

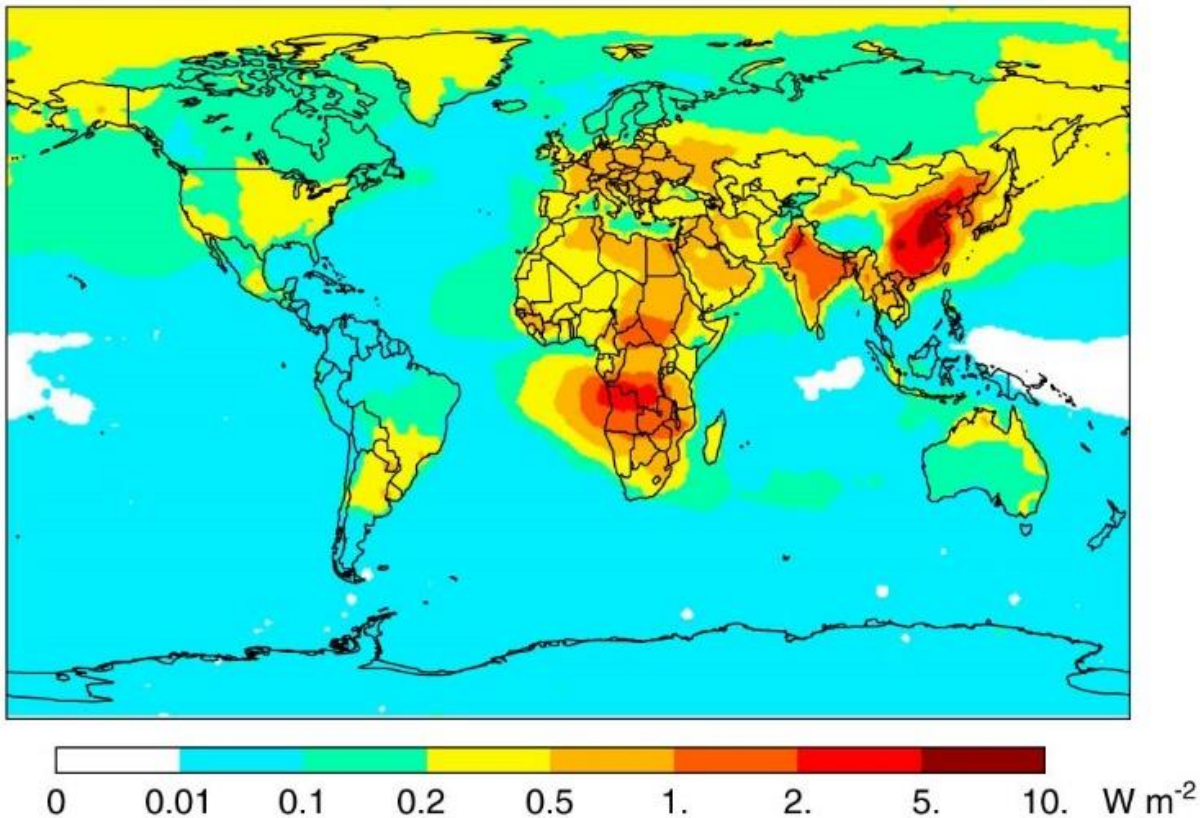


Aerosol optical depths (i.e. a measure of atmospheric transparency) for black carbon (BC, x10) (a) in 1890, (b) in 1995, and (c) the change between 1890 and 1995; (d)–(f) the same measures for sulphates. Reproduced from Koch et al. (2008).

Major Radiative forcing agents

Aerosols

The net aerosols forcing is negative but some aerosols induce a positive forcing.

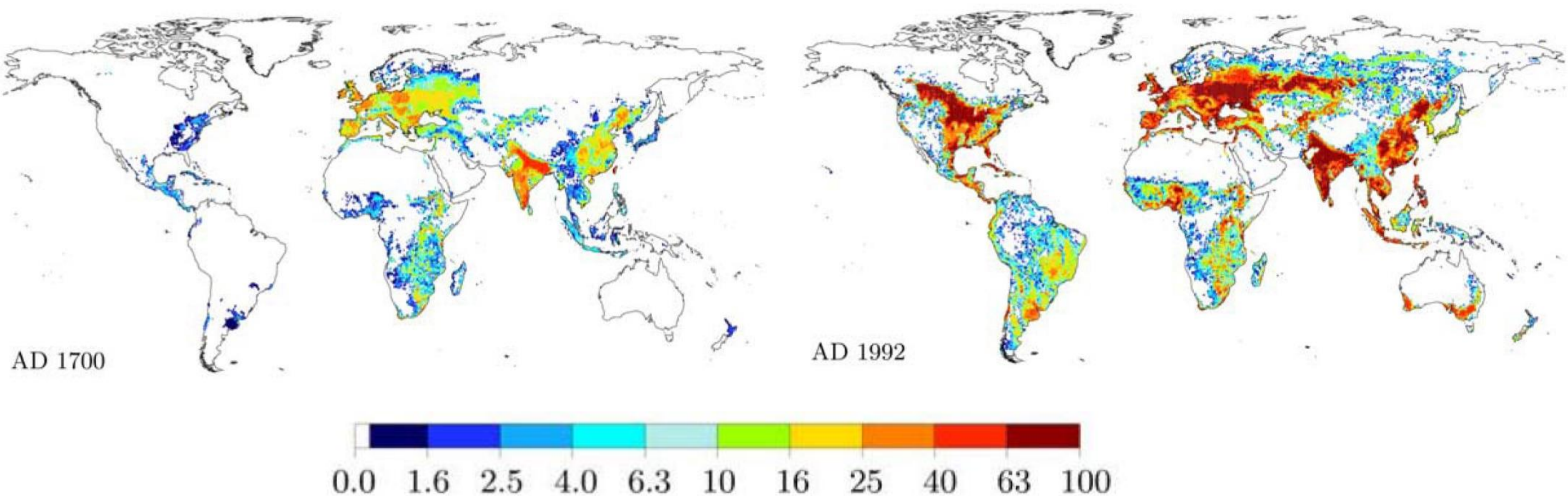


Estimate of annual mean forcing due to of black carbon in 2009 (Wang et al. 2014).

Major Radiative forcing agents

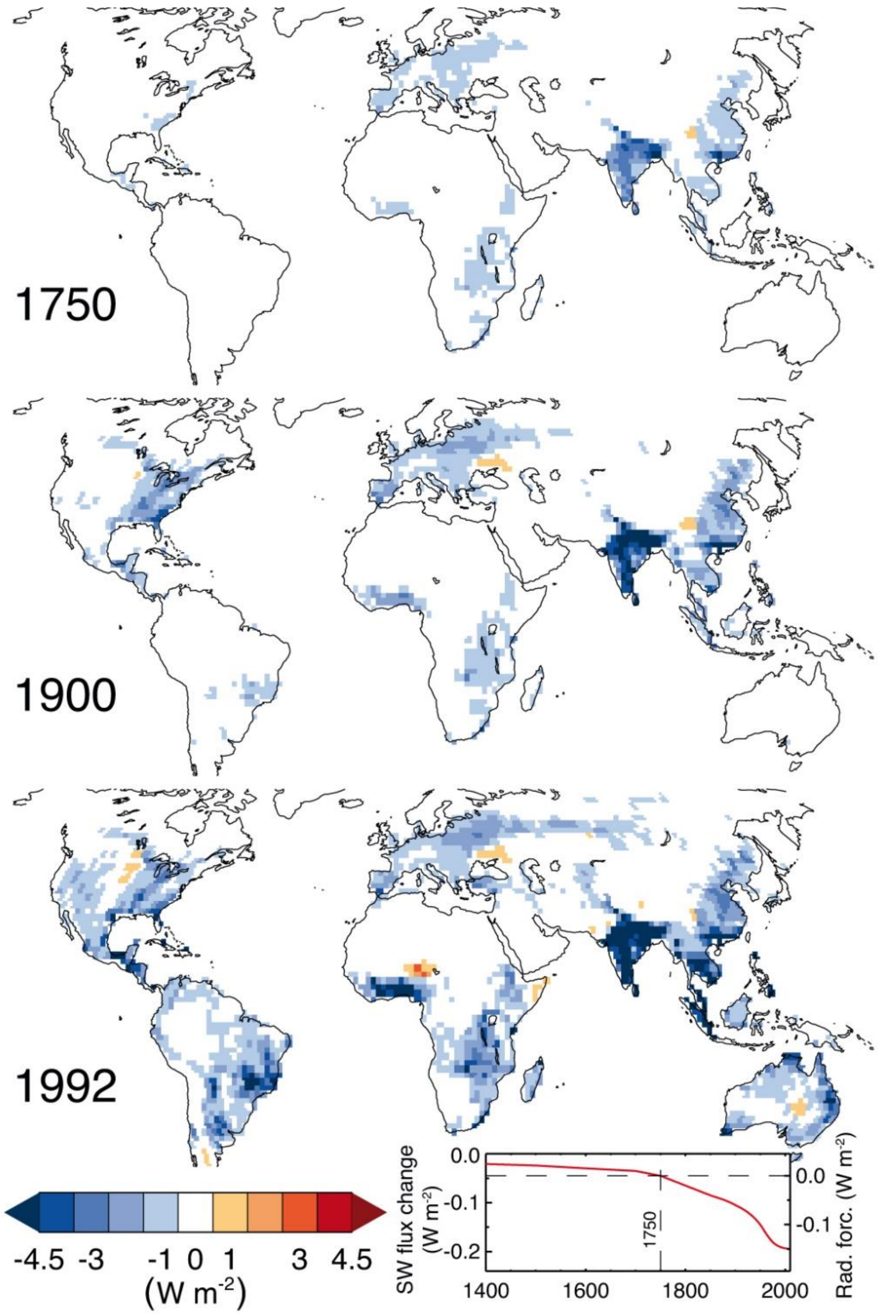
Land use and land cover changes

- Direct impact on emissions of CO_2 and CH_4 and aerosols.
- Modification of the characteristics of the Earth's surface.



The fraction of land occupied by crops in 1700 and 1992. Figure from Pongratz et al. (2008).

Major Radiative forcing agents



Land use and land cover changes: radiative forcing

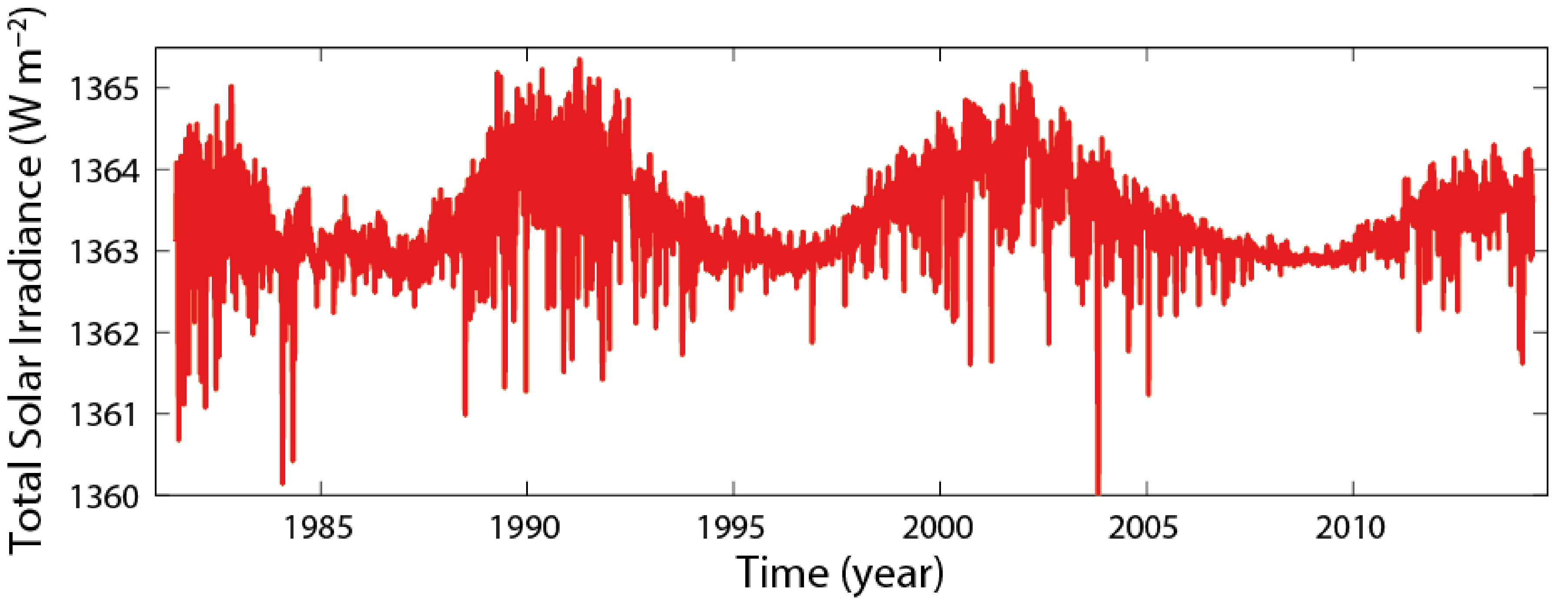
Change in top of the atmosphere shortwave (SW) flux (W m^{-2}) following the change in albedo as a result of anthropogenic land use change.

Figure from Myhre et al. (2013), based on simulations by Pongratz et al. (2009).

Major Radiative forcing agents

Solar and volcanic forcings

Changes in total solar irradiance

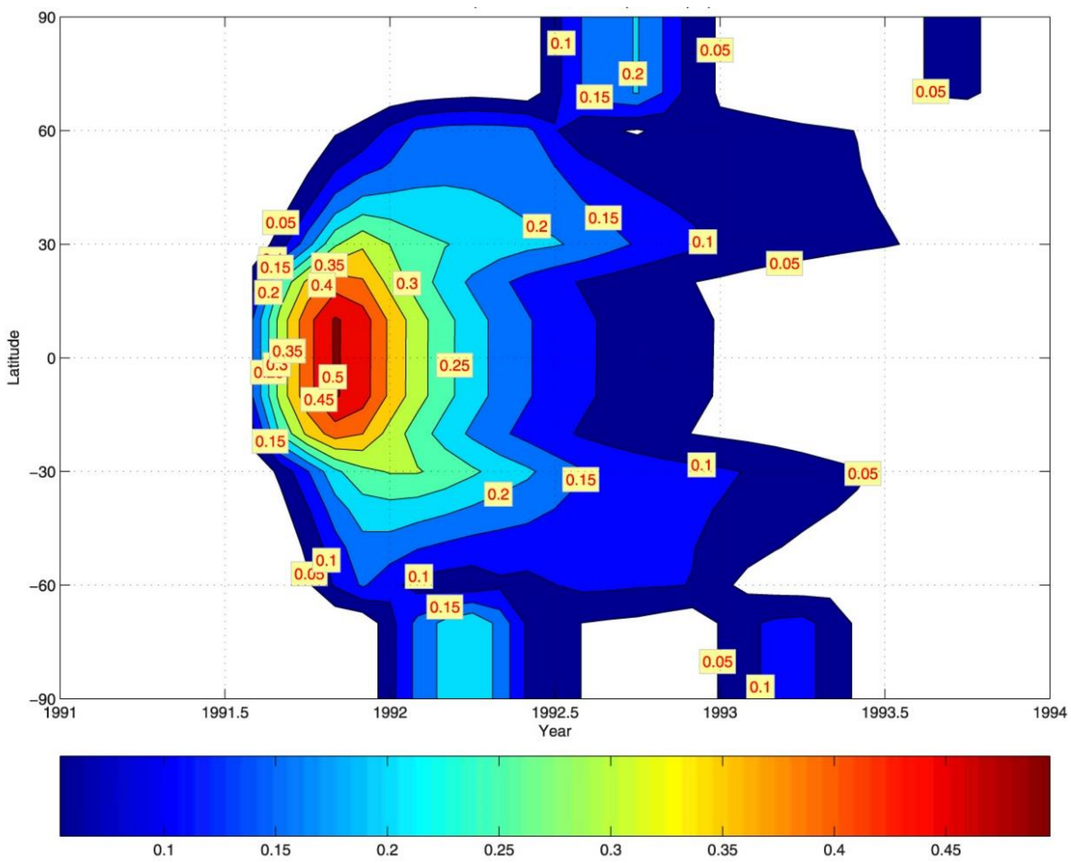


Changes in total solar irradiance estimated from a composite of measurements performed with different satellites (RMIB TSI composite, Mekaoui and Dewitte, 2008 and updates).

Major Radiative forcing agents

Solar and volcanic forcings

Explosive volcanic eruptions can transport aerosols directly to the stratosphere where they remain for a few years.



Estimate of the volcanic aerosol optical depth after the 1991 Pinatubo eruption as a function of latitude and time. Figure from Gao et al. (2008).

Definition of feedback

The imbalance in the radiative budget can be expressed as a function of the changes in global mean surface temperature, ΔT_s.

$$\Delta R = \Delta Q + \lambda_f \Delta T_S$$

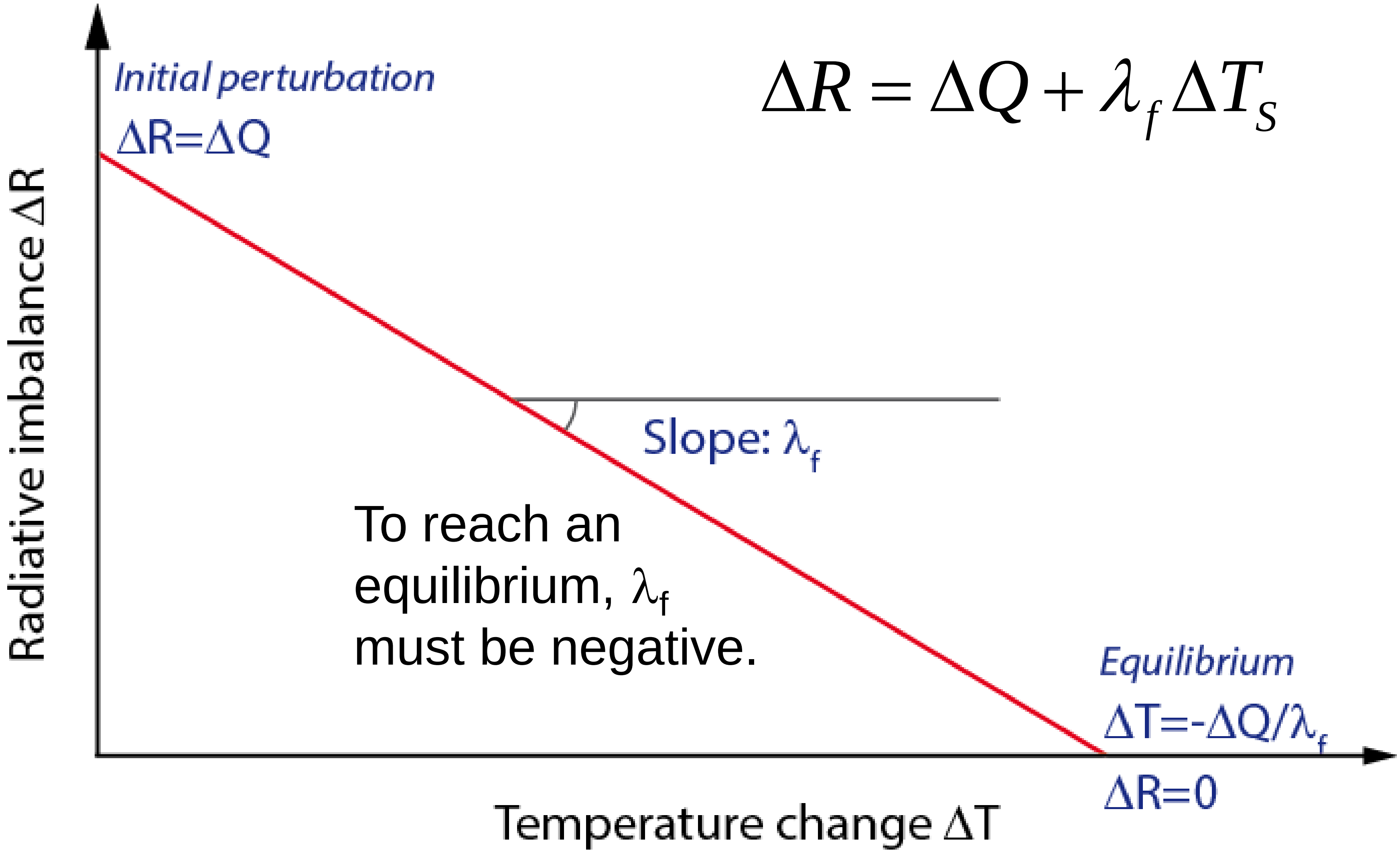
Imbalance in the radiative budget

Radiative forcing

Climate feedback parameter (expressed in W m^{-2} K^{-1}).

Definition of feedback

$$\Delta R = \Delta Q + \lambda_f \Delta T_S$$



Schematic representation illustrating the role of the climate feedback parameter λ_f

Definition of feedback

The equilibrium climate sensitivity is defined as the global mean surface temperature change after the climate system has stabilized in a new equilibrium state in response to a doubling of the CO_2 concentration in the atmosphere.

$$\Delta T_S = -\frac{1}{\lambda_f}\Delta Q = -\frac{3.7}{\lambda_f}$$

The equilibrium climate sensitivity is measured in °C and its value is likely to be in the range 1.5-4.5°C.

Direct physical feedbacks

λ_f could be represented by the sum of different feedback parameters.

$$\lambda_f = \sum_i \lambda_i = \lambda_0 + \lambda_L + \lambda_w + \lambda_c + \lambda_\alpha$$

Blackbody response

Lapse rate feedback

Water vapour feedback

Cloud feedback

surface albedo feedback

Direct physical feedbacks

λ_0 can be evaluated relatively easily using integrated balance at the top of the atmosphere:

$$R = (1-\alpha)\frac{S_0}{4} - \sigma T_E^4$$

This leads to:

$$\lambda_0 = \frac{\partial R}{\partial T} = -4\sigma T_E^3 \simeq \text{ -3.2 W m}^{-2}\text{ K}^{-1}$$

If this feedback was the only one active:

$$\Delta T_{S,0} = -\frac{\Delta Q}{\lambda_0} \approx 1°C \text{ for a doubling of the CO}_2\text{ concentration}$$

Direct physical feedbacks

If all the feedbacks are active:

$$\Delta T_S = -\frac{\Delta Q}{\sum_i \lambda_i} = -\frac{\Delta Q}{\lambda_0 + \lambda_L + \lambda_w + \lambda_c + \lambda_\alpha}$$

$$\Delta T_S = \frac{1}{\left(1 + \frac{\lambda_L}{\lambda_0} + \frac{\lambda_w}{\lambda_0} + \frac{\lambda_c}{\lambda_0} + \frac{\lambda_\alpha}{\lambda_0}\right)} \Delta T_{S,0}$$

A negative value of a feedback parameter reduce the equilibrium temperature change compared to the blackbody response.

Transient response of the climate system

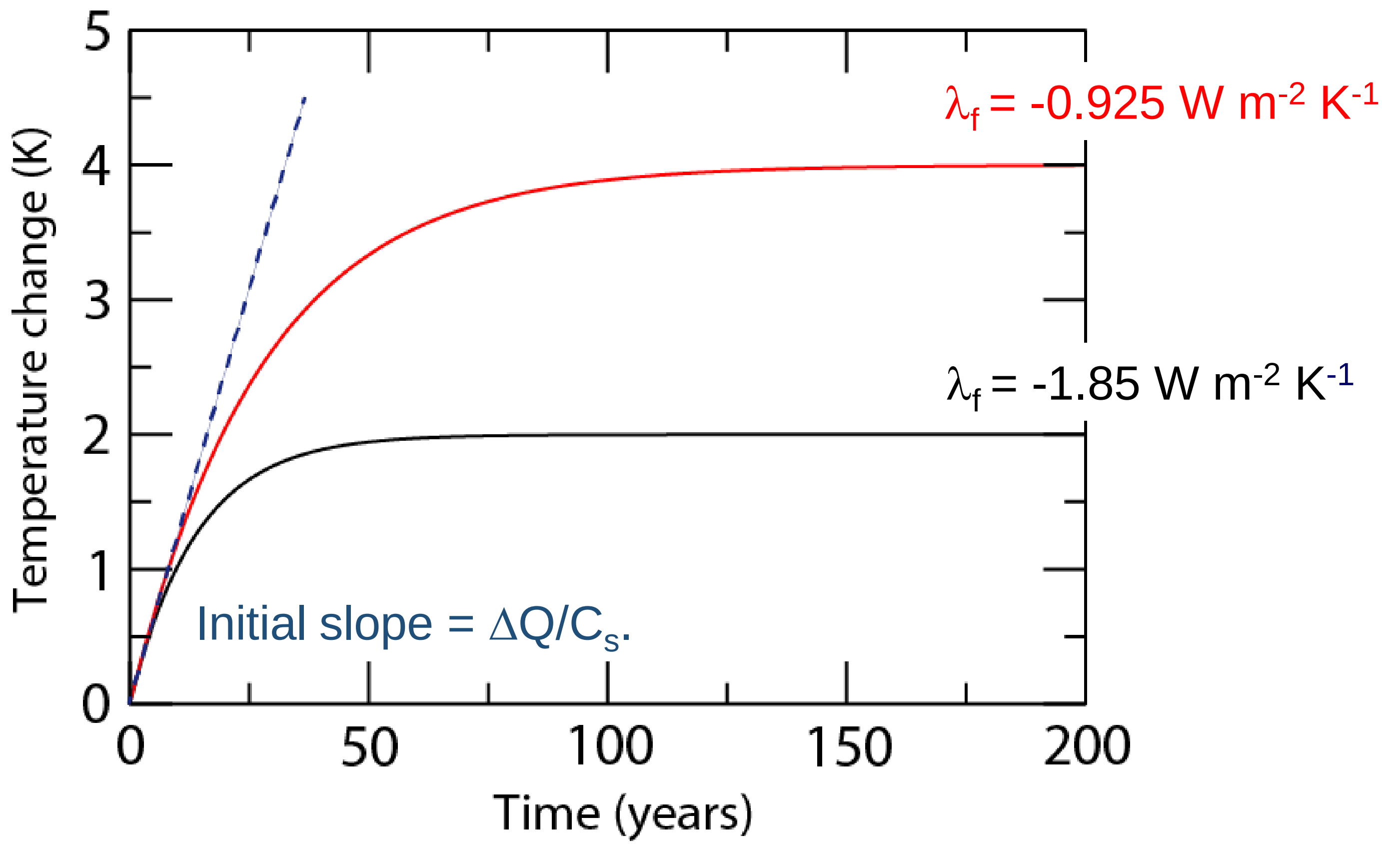
The equilibrium response is achieved when all the components of the system have adjusted to the new forcing (ocean heat uptake).

Transient response:

$$C_s \frac{d\Delta T_S}{dt} = \Delta Q + \lambda_f \Delta T_S$$

Thermal inertia
of the system

Transient response of the climate system



Transient temperature changes obtained using a forcing ΔQ of 3.7 W m-^{2} and C_s equal to 8.36 10^8 J K^{-1} m^{-2}

Transient response of the climate system

In some cases, the ocean heat uptake is roughly proportional to ΔT_s.

The heat balance becomes:

$$\kappa_c \Delta T_S = \Delta Q + \lambda_f \Delta T_S$$

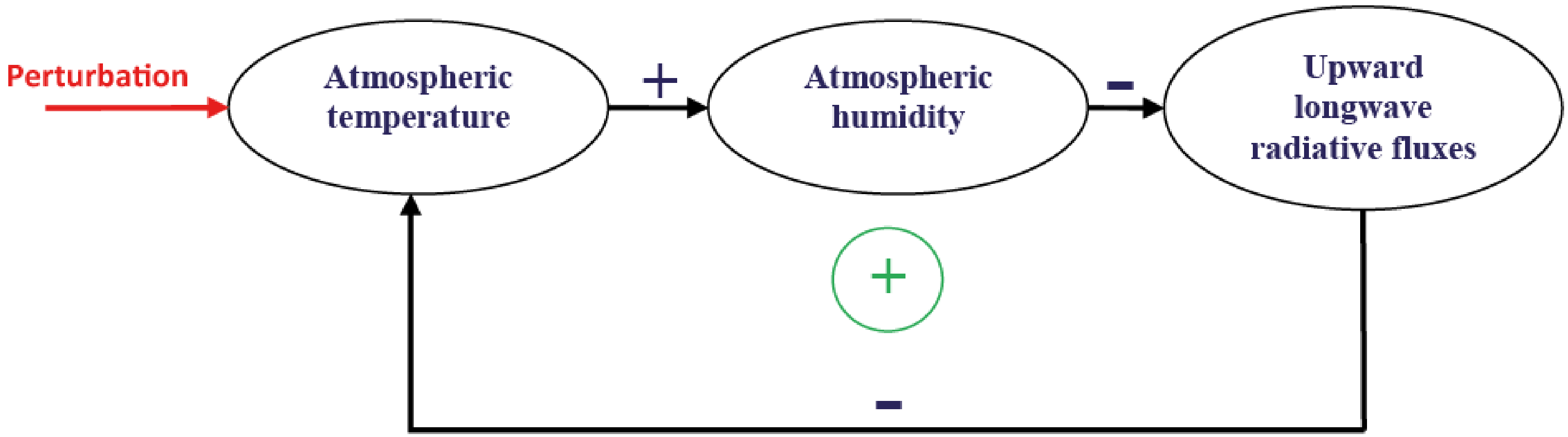
Ocean heat uptake efficiency (W m^{-2} K^{-1}).

In this framework, the heat uptake can be interpreted as equivalent to a negative feedback : $\kappa_c \approx 0.6 \mathrm{W\ m^{-2} K^{-1}}$

Water vapour feedback

The increase in the amount of water vapour in the atmosphere due to a warming leads to a strong positive feedback.

$$\lambda_w \approx 1.6 \mathrm{W\ m^{-2} K^{-1}}$$

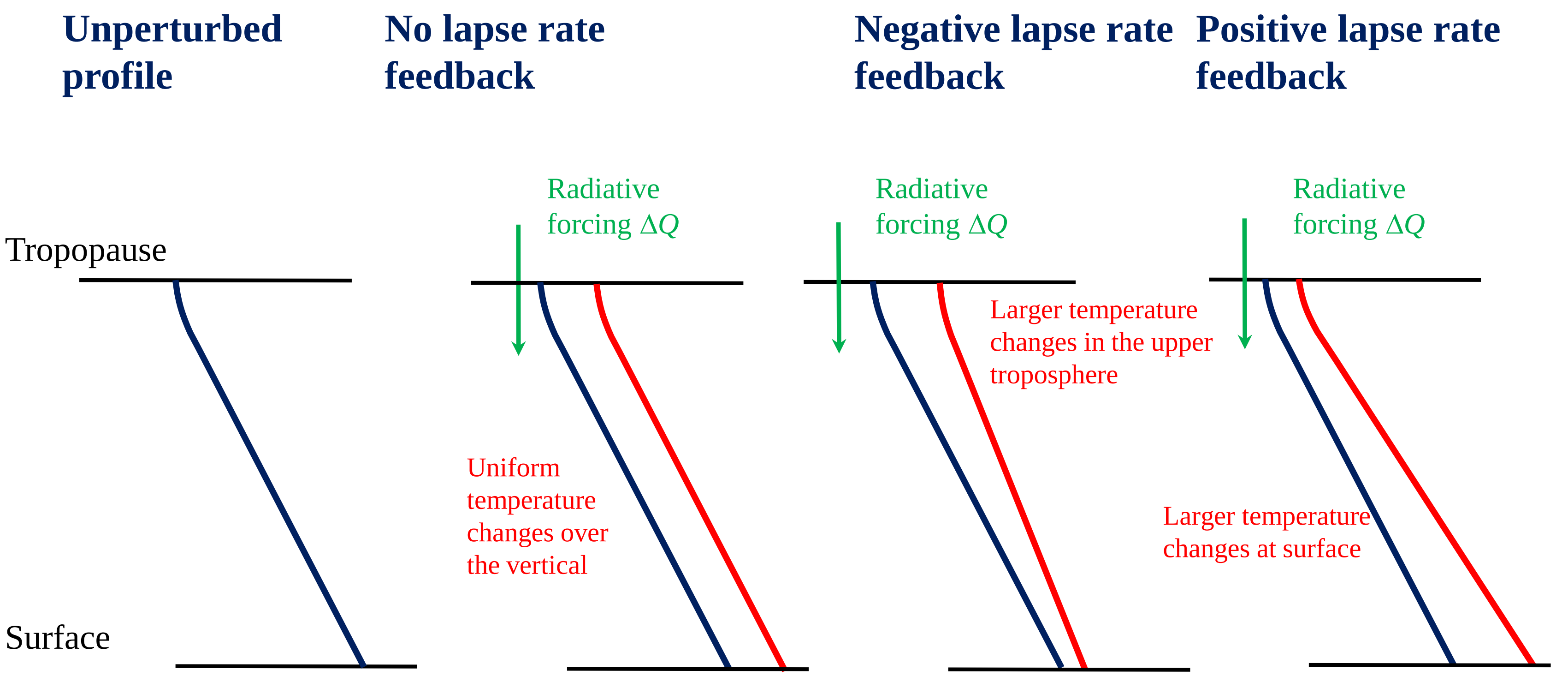


Simplified signal flow graph illustrating the water vapour feedback. A positive sign on an arrow means that the sign of the change remains the same when moving from the variable at the origin of the arrow (on the left in the top row) to the one pointed by the arrow (on the right in the top row) while a negative sign implies that an increase (decrease) in one variable induces a decrease (increase) in next one. The positive sign in a circle indicates that the overall feedback is positive.

Lapse rate feedback

The vertical variations of the temperature change have a climatic effect that vary between regions.

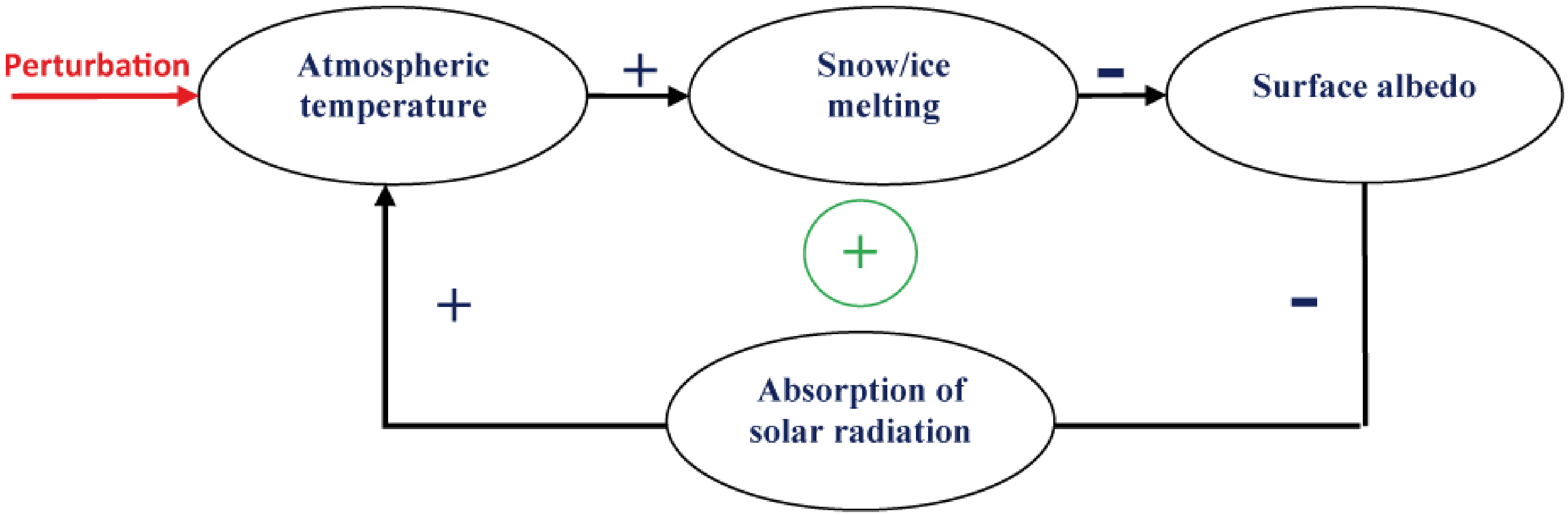
$$\lambda_w \approx -0.6 \mathrm{W\ m^{-2} K^{-1}}$$



Cryospheric feedbacks

The presence of ice or snow at the surface strongly modifies the albedo: snow-and-ice albedo feedback.

$$\lambda_\alpha \approx 0.3\,\mathrm{W\,m^{-2}K^{-1}}$$



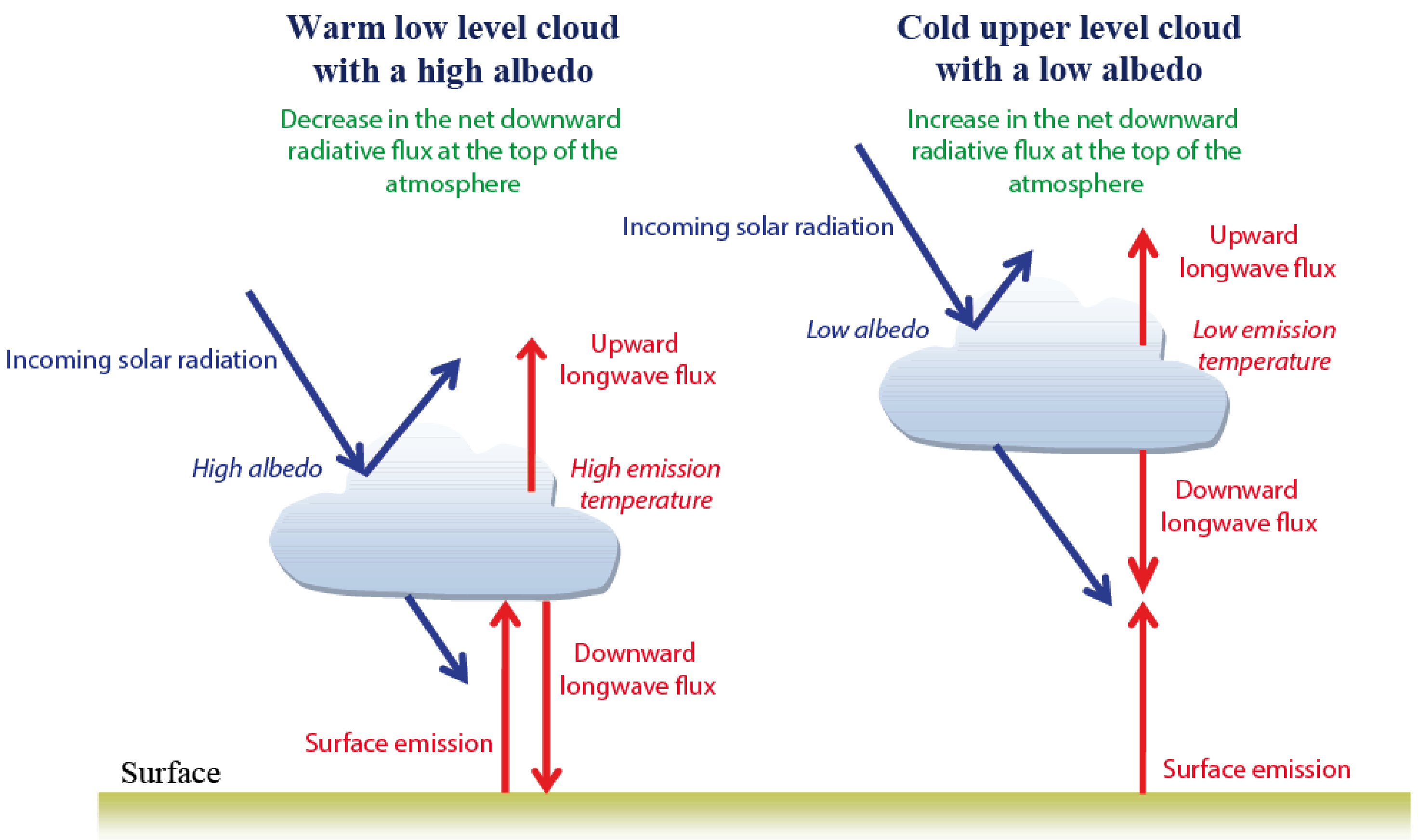
Other cryospheric feedbacks are also important, related to the insulation effect of sea ice or to the formation of ice sheets.

Cloud feedbacks

Clouds strongly affects the Earth energy budget.

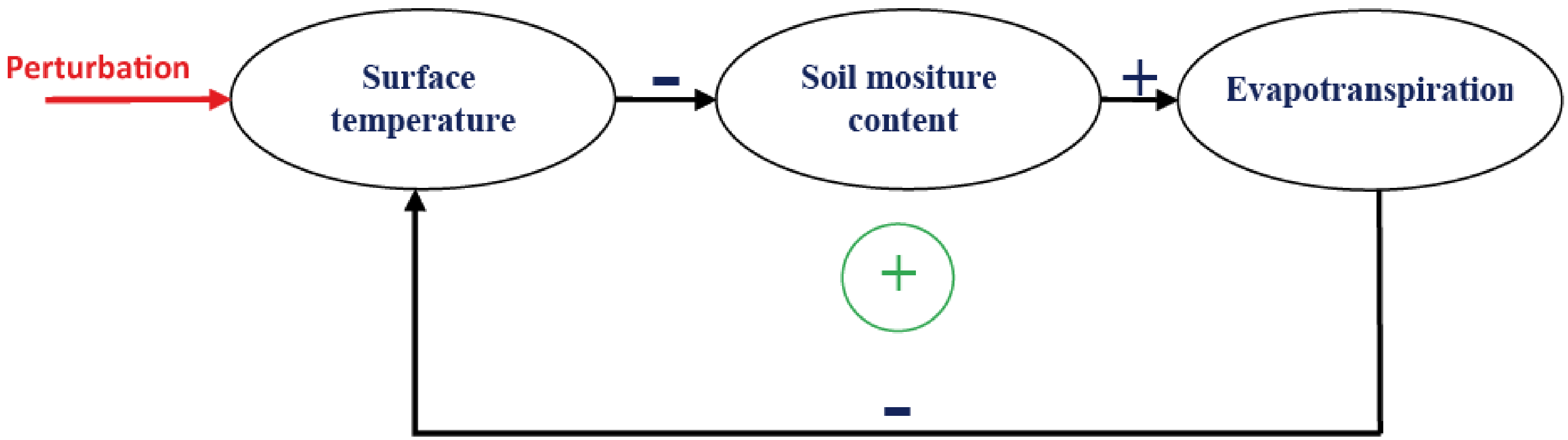
The magnitude of cloud feedbacks is uncertain.

$$\lambda_c \approx 0.3 \mathrm{W\ m^{-2} K^{-1}}$$



Soil-moisture climate feedbacks

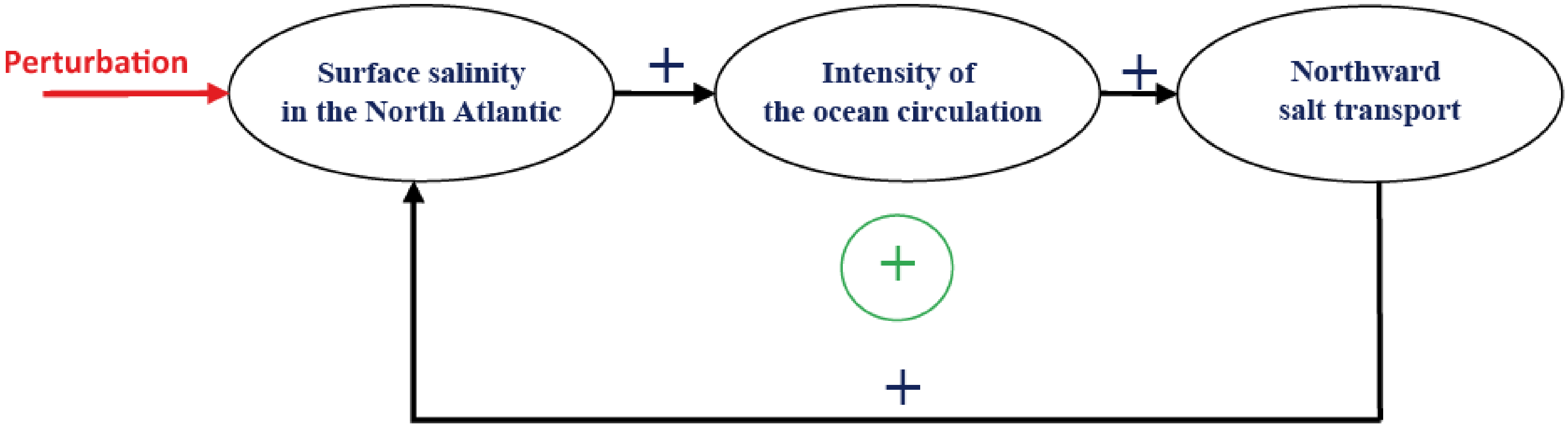
Changes in soil moisture content affect the surface heat fluxes.



Changes in soil moisture content can also affect precipitation.

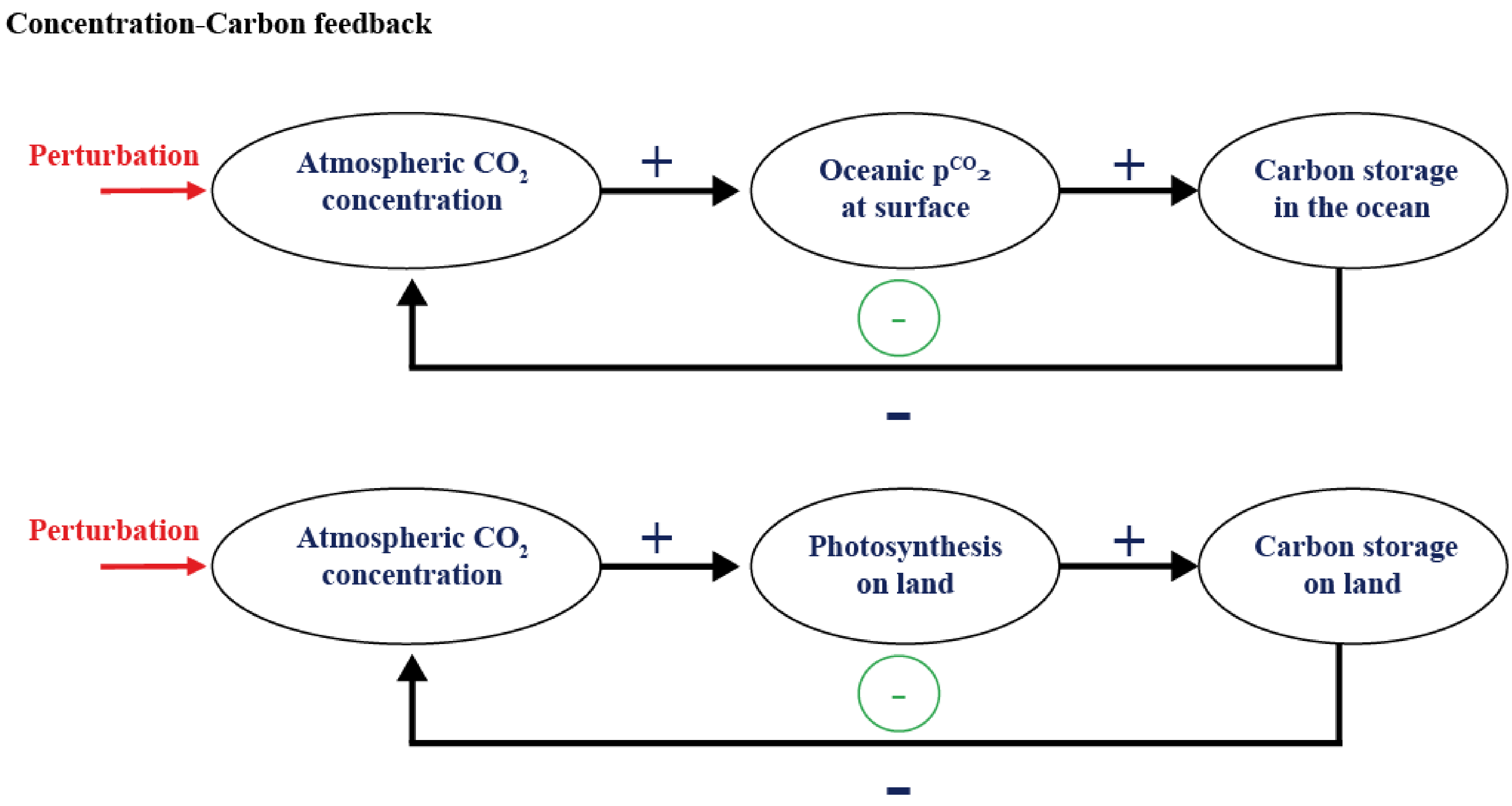
Advective feedback in the ocean

A perturbation of the freshwater budget of the North Atlantic can be amplified by ocean circulation changes.



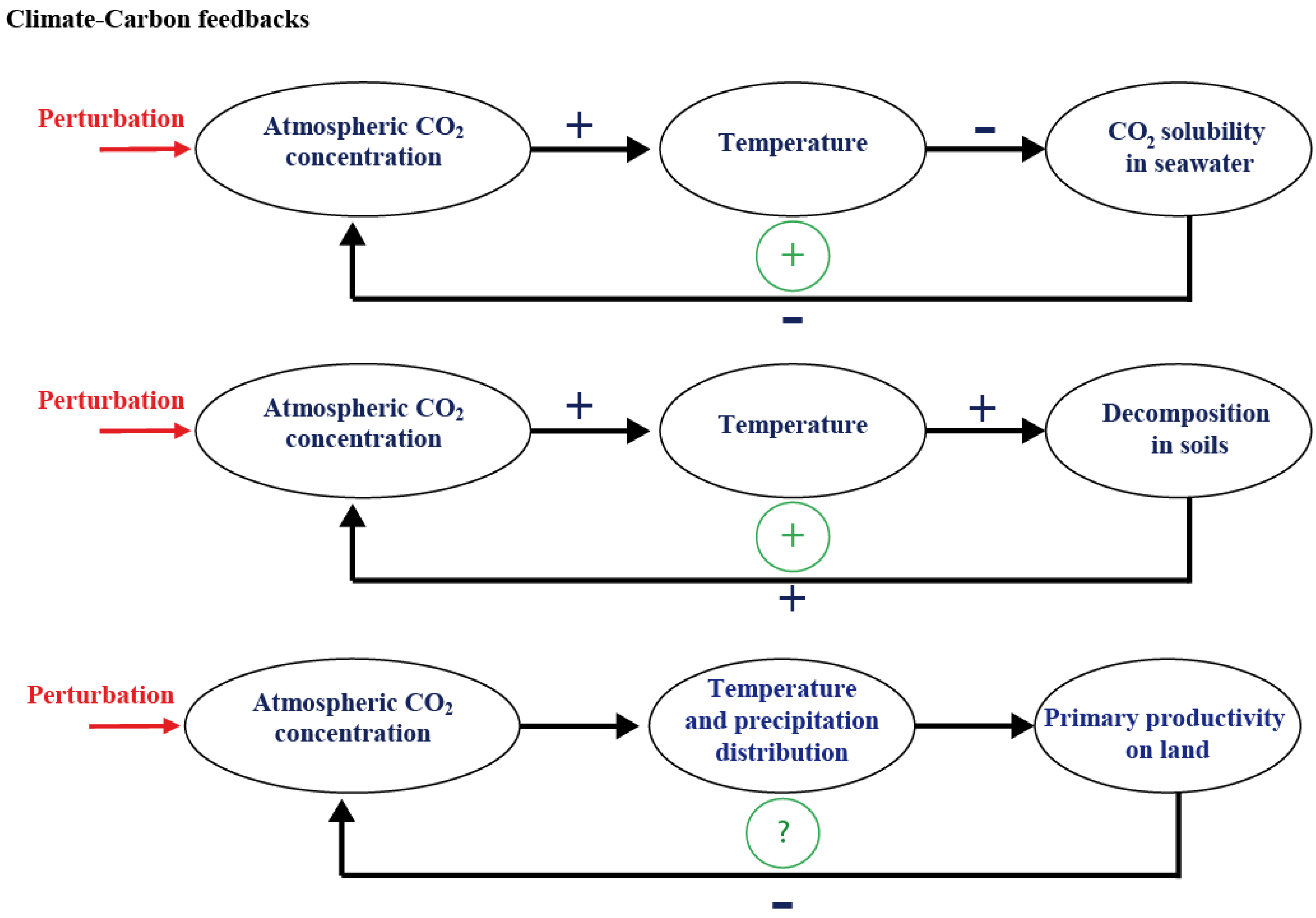
Biogeochemical and biogeophysical feedbacks

Some biogeochemical feedbacks are present even in the absence of any climate change.



Biogeochemical and biogeophysical feedbacks

Some biogeochemical feedbacks are related to climate changes.



Biogeochemical and biogeophysical feedbacks

Concentration-carbon feedback and the climate-carbon feedback parameters

$$C_E = \Delta C + \Delta C_O + \Delta C_L$$

Carbon emission

Change in atmospheric carbon content

Change in oceanic carbon content

Change in carbon storage over land

Biogeochemical and biogeophysical feedbacks

Concentration-carbon feedback and the climate-carbon feedback parameters.

$$C_E = \Delta C + \beta \Delta C + \gamma \Delta T$$

Carbon emission

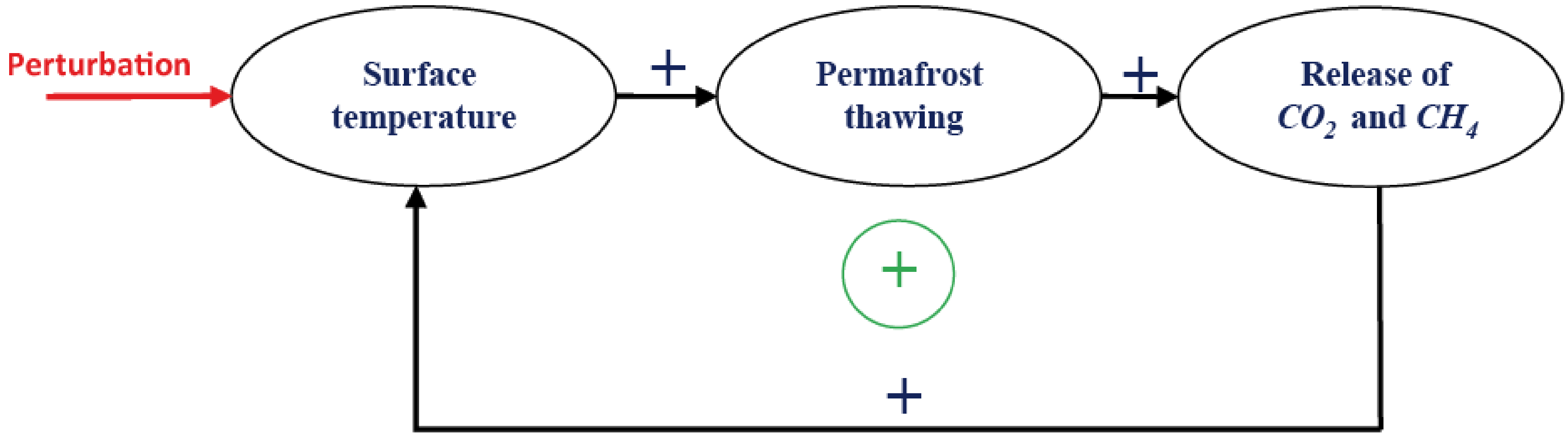
Change in atmospheric carbon content

Concentration-carbon feedback

Climate-carbon feedback

Biogeochemical and biogeophysical feedbacks

Feedbacks involving permafrost and methane.



Biogeochemical and biogeophysical feedbacks

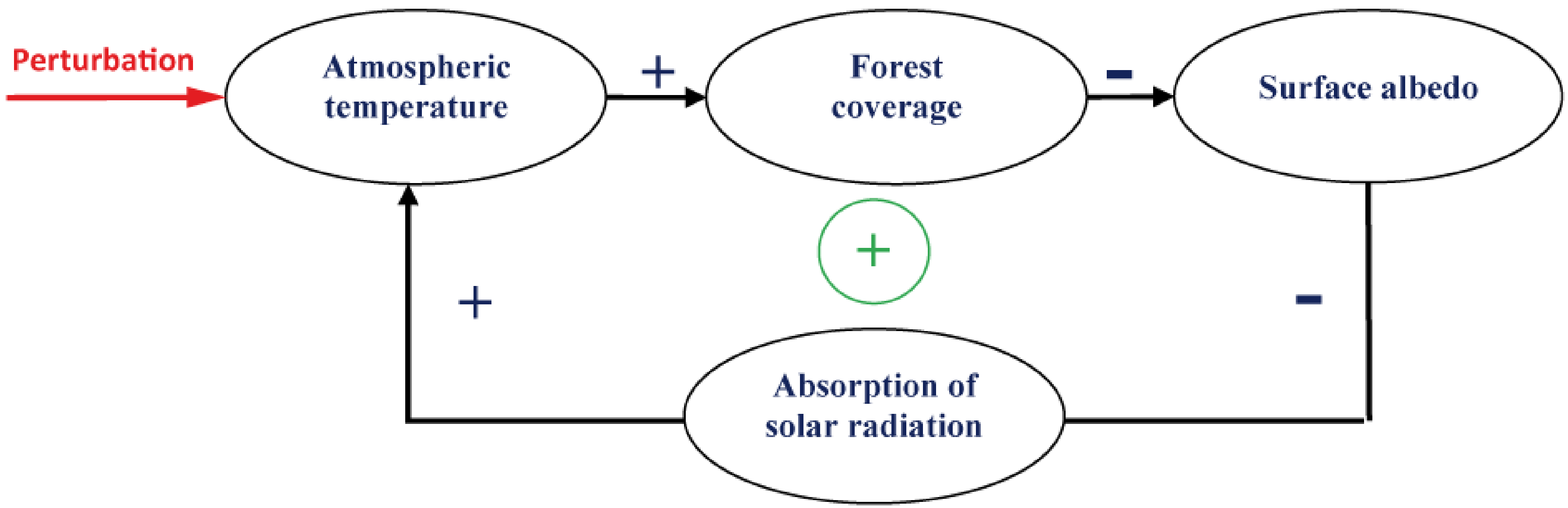
Interactions between climate and the terrestrial biosphere.

The albedo of a snow covered forest is much lower than the one of snow over grass.

Biogeochemical and biogeophysical feedbacks

Interactions between climate and the terrestrial biosphere.

Tundra-Taïga feedback.



Biogeochemical and biogeophysical feedbacks

Some feedbacks act on long timescales.

The carbonate compensation.

A stabilising feedback between the oceanic carbon cycle and the underlying sediment allows a balance between the source of calcium carbonate due to weathering and the sink due to sedimentation.

Biogeochemical and biogeophysical feedbacks

The carbonate compensation.

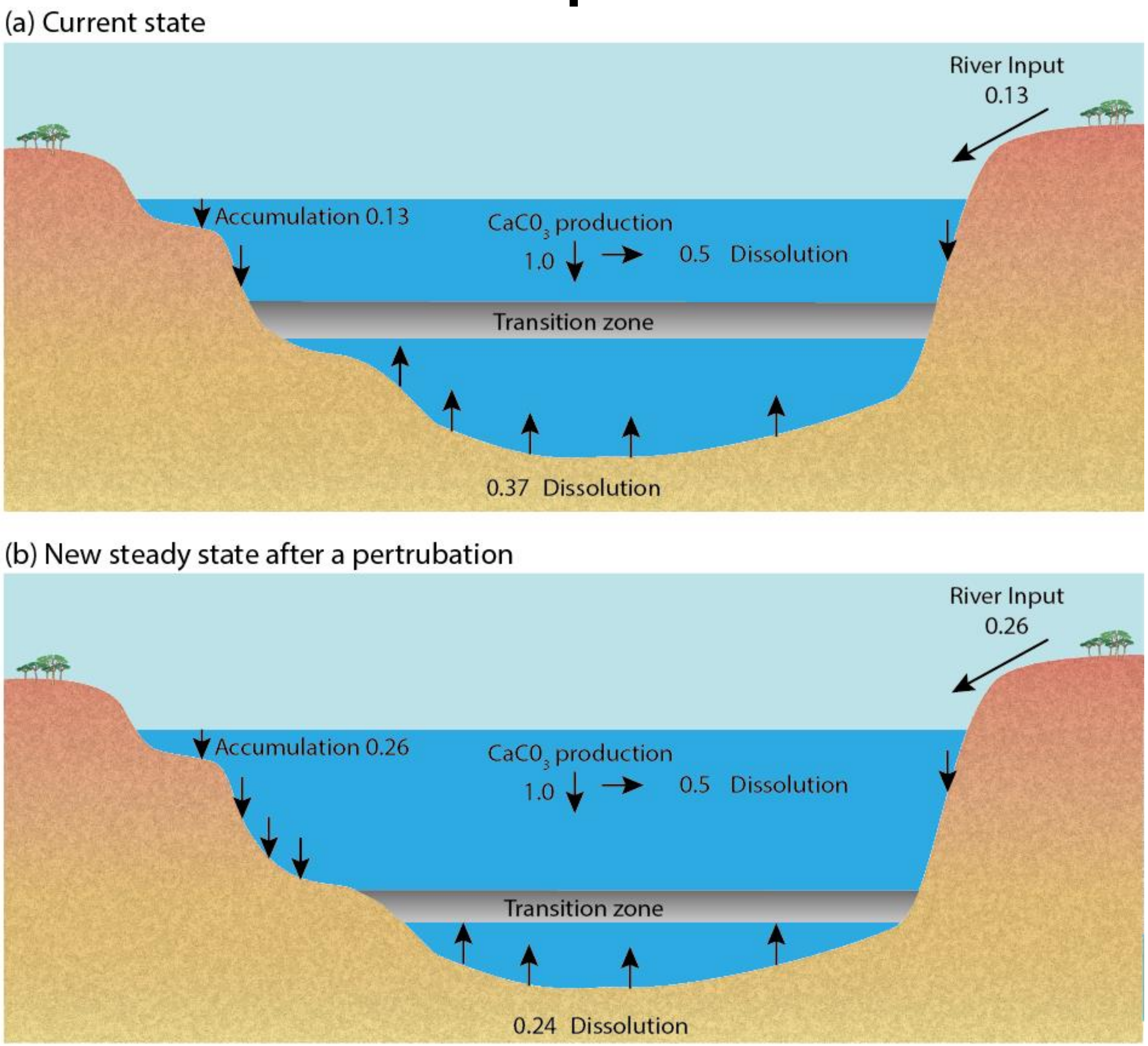
The saturation of calcium carbonate is mainly influenced by the carbonate concentration.

$$K^{CaCo_3} = \left[CO_3^{2-}\right]_{sat} \left[Ca^{2+}\right]_{sat}$$

Carbonate concentration decreases with depths and solubility increases with pressure.

➡ The upper ocean is supersaturated while the deep ocean is undersaturated. The depth at which those two regions are separated is called the saturation horizon.

The carbonate compensation.

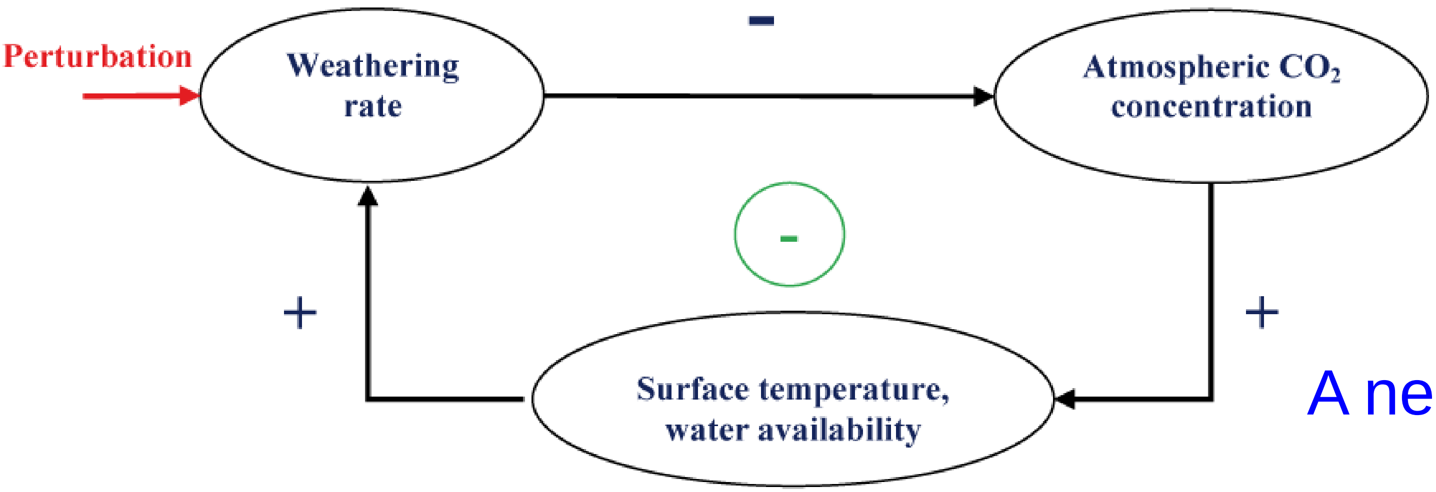


If the river input of calcium carbonate is doubled, the saturation horizon deepens, leading to less dissolution and more accumulation in the sediments in order to reach a new balance.

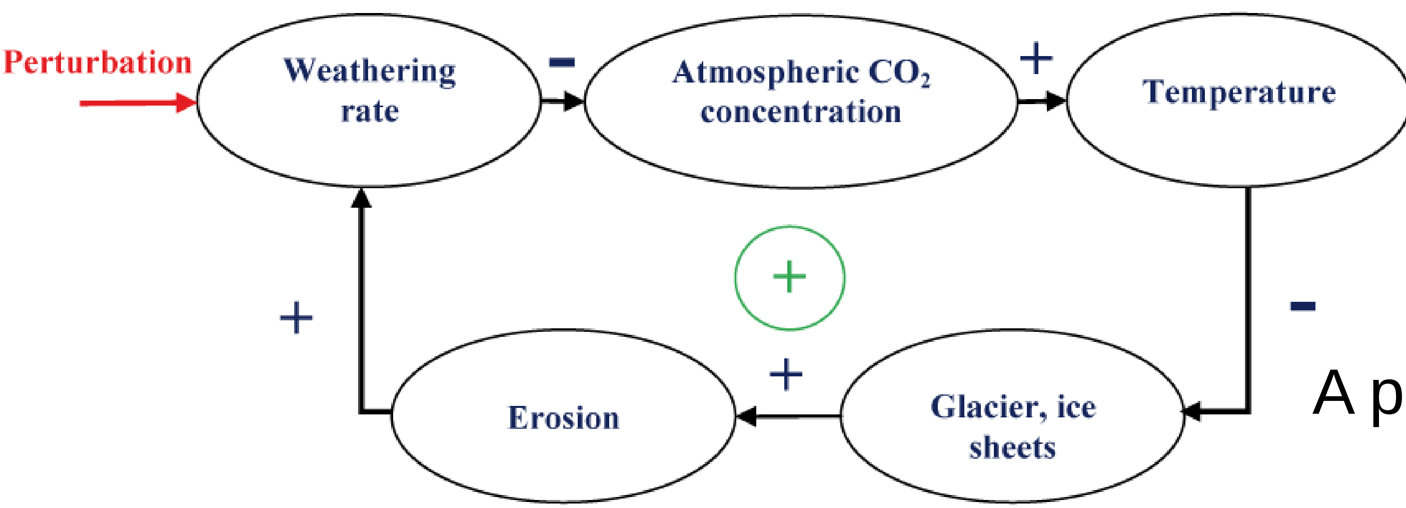
Figure based on Sarmiento and Gruber (2006).

Biogeochemical and biogeophysical feedbacks

Interaction between plate tectonics, climate and the carbon cycle.



A negative feedback



A positive feedback

Additionnal reference:

Wang, Q., D. J. Jacob, J. R. Spackman, A. E. Perring, J. P. Schwarz, N. Moteki, E. A. Marais, C. Ge, J. Wang, and S. R. H. Barrett (2014), Global budget and radiative forcing of black carbon aerosol: Constraints from pole-to-pole (HIPPO) observations across the Pacific, J. Geophys. Res. Atmos., 119, 195–206, doi:10.1002/2013JD020824.